Studies of Energy Transfer Between Crossing Laser Beams in Plasmas

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Introduction

The amplification of light by the parametric decay of a laser beam propagating in a plasma has been studied since the inception of the inertial confinement fusion (ICF) program, primarily because it is a mechanism for scattering and loss of the laser's energy. Recent studies[1] show that the resonant nonlinear processes which excite plasma waves and lead to stimulated Raman and Brillouin scattering (SBS and SRS)[2] can also lead to the transfer of energy between laser beams under the right conditions. This stimulated energy transfer is analogous to four-wave mixing in nonlinear media,[3] although standard optics treatments do not include the propagation velocity of the plasma waves which affect the frequency matching conditions and limit the energy transfer. In past ICF experiments, symmetric illumination of the target has worked to prevent energy transfer between beams. In the National Ignition Facility (NIF), however, laser beams with different intensities and different angles of incidence will cross at the hohlraum entrance, where energy transfer may occur. Such energy transfer would be detrimental to the implosion symmetry and fusion yield. We have performed a series of experiments using the Nova facility to understand and control these effects.

The process by which light is transferred between two beams is the same as the process by which stimulated scattering grows from thermal noise. In both cases, the incident laser beam decays into an electrostatic wave, propagating in the plasma, and a scattered electromagnetic wave. The decay is initiated when it is "seeded" by a source of one of the decay waves. For stimulated scattering experiments, the seed wave is a very low amplitude electrostatic or electromagnetic wave that is generated by thermal noise, while in crossing beam experiments the seed wave is a second laser beam. The interaction of crossing beams is obviously favored over stimulated scattering because the initial seed is large and only a small amplification factor will result in substantial transfer of energy. However, the symmetry of the crossed beam interaction has suppressed the effect in previous ICF experiments in which the crossing laser beams had identical intensities, as well as identical incident angles. With identical beams in a stationary plasma, there can be no net energy transfer. Furthermore, the stimulated process can only occur when the incident and seed waves have different frequencies in the frame of the plasma, with fastest growth occurring when the difference frequency is equal to that of the resonant plasma wave. Thus, either a frequency difference between the incident and seed waves, or a plasma flow that Doppler shifts the frequency of one of the waves relative to the other, can allow the stimulated process to occur and transfer significant energy. In the NIF, the beams will be required to have different intensities and different incident angles, which results in different frequences in the frame of the flowing plasma, thus allowing for the possibility of resonant energy transfer between the beams.

To simulate the interaction of the four-color beams in NIF, we performed a series of experiments on Nova to study the transfer of energy between beams with slightly mismatched frequencies in a nearly stationary but otherwise NIF-like plasma. In these experiments, the frequency mismatch was achieved by tuning the frequency of the incident beam rather than relying on Doppler shifts from plasma flows. For the first time, the amplification of a probe laser beam by interaction with a second frequency shifted (pump) beam and a stimulated ion acoustic wave was observed. The amplification of the long wavelength (probe) laser beam reaches a maximum of 2.8 when the frequency difference $\Delta\omega$ of the two beams is in the vicinity of the ion acoustic resonance ($\Delta\omega = c_s\,|\Delta\mathbf{k}|$). Here, c_s is the acoustic speed and $\Delta\mathbf{k}$ **is** the difference in wave vectors between the two beams. The amplification is steady state in that it persists for many ($\sim10^3$) ion acoustic periods and is resonant in that it is largest at a particular frequency difference. In addition, in the large, mixed species plasmas that are used in these experiments, we find that the amplification of the probe beam is independent of its intensity (up to a maximum average scattered intensity of 1.0×10^{15} W/cm^2). This indicates that the ion wave response n_1 remains unsaturated up to $n_1/n_0 \sim 1\%$, where n_0 is the unperturbed density.

Experimental Setup

The experiments were performed in an approximately spherical plasma[4] produced by eight f/4.3, $\lambda = 351$ nm beams. These heater beams have a 1 ns, square pulse shape with a total power of 20 TW (2.5 TW each beam) and pass through a 1 atm C_5H_{12} gas contained in a 500-nm-thick spherical polyimide shell with radius $r_0 = 1.3$ mm. Each heater beam is centered at the target center with a converging focus. The beam spot size at the target center is approximately equal to the target diameter, allowing spatially uniform heating. Two dimensional (2-D) numerical simulations using LASNEX[5] indicate that after $t = 400$ ps, a stationary plasma is formed (velocity $\leq 0.15\ c_s$), with a uniform density plateau ($\Delta n/n \leq 0.1$) in the region between $r = 250$ and 900 μm. By 1.4 ns after the beginning of the heater beam pulse, the outer edge of the plateau region has shrunk to approximately $r = 450$ μm by an incoming shock wave created by the ablation of the polyimide shell. The plasma parameters calculated by the simulation, and in agreement with measurements[4] are: electron density of $n_e = 10^{21}$ cm^{-3} (0.1 n_c, where n_c is the critical density for $\lambda = 351$ nm light) and electron temperature $T_e = 3.0$ keV.

The high-intensity pump beam and low-intensity probe beam are also f/4.3 and $\lambda_o = 351$ nm, and are aligned to cross at $r = 400$ μm near best focus for both beams. As a result, the interaction between the two electromagnetic waves occurs in the plateau region of the plasma, as shown in Fig. 1. This allows the ion wave that is driven by the beating of the two beams to propagate in a plasma in which gradients are minimized. The interaction beams have random phase plates (RPPs) which smooth the intensity profile and limit the spot size to 177 μm full-width half maximum (FWHM) (345 μm between first Airy minima) and the peak pump intensity to 1×10^{16} W/cm^2 (2×10^{15} W/cm^2 average inside the Airy minima) in vacuum. The beams have their polarizations aligned within 25° of parallel. The simulations indicate that the presence of the focused probe beam increases the temperature only slightly (~6%) in the vicinity of best focus.

The probe beam is adjusted to have a wavelength slightly longer than that of the pump with the wavelength separation ranging between 0.0 and 0.73 nm. The pump beam frequency is 10,527.7Å (1ω). The technique used to provide the tunable frequency probe beam is based on nonlinear mixing of the two frequencies in an optical fiber prior to injection into the laser chain.[6] Two photons at different pump frequencies mix together to create a comb of single frequency sidebands separated by the difference frequency between the two initial pump frequencies. The pump frequencies are produced by two Q-switched neodymium-doped yttrium lithium fluoride oscillators. The difference frequency is variable from 0.1–4.5 Å by tuning one of the oscillator frequencies via an intracavity etalon. The total number of frequencies produced is controlled by varying the oscillator intensities into the fiber. The probe frequency of interest is selected with a grating monochrometer located in the Nova preamplifier section and is frequency tripled (3ω) by potassium dihydrogen phosphate crystals after amplification. While up to 260 Å of bandwidth (FWHM) can be generated with the fiber-optic technique at 1ω, the maximum usable frequency range is ~32 Å due to gain narrowing in the laser amplifier chain, limiting the maximum frequency separation of the converted beam to 10.7 Å at 3ω.

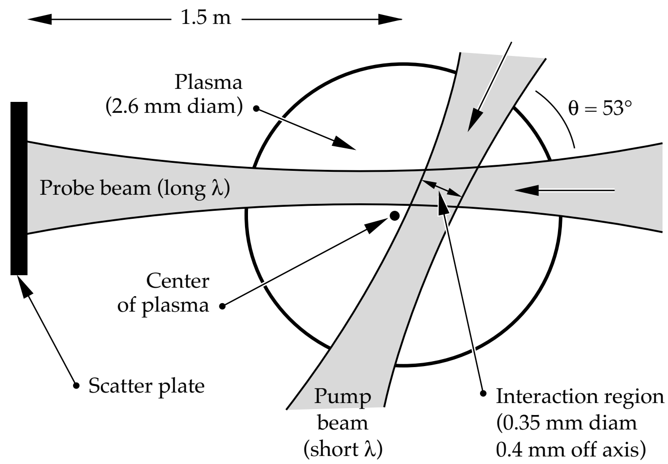

FIGURE 1. Experimental configuration showing an approximately spherical plasma and two interaction beams crossing in a homogeneous region off the plasma center. The two beams are detuned by $\Delta\lambda = 0.0$ to 0.73 nm to excite the ion acoustic resonance. The transmitted power vs time of the long wavelength probe beam is measured. (08-00-0296-0343pb01)

The probe beam has a square pulse shape lasting 2.0 ns, which begins at the same time as the heaters ($t = 0$). The pump beam has a 1.0 ns square pulse shape that is delayed 0.4 ns so that the plasma in the interaction region is relatively homogeneous during the interaction period. The transmitted power of the probe beam is collected by a fused silica plate 1.5 m from the target, which is roughened to scatter the light over a broad angle.[7] This scattered light is imaged onto a fast photodiode and a gated optical imager. The photodiode is calibrated to provide a histogram of the probe beam power, which is transmitted through the plasma and onto the scatter plate. The imager captures a 2-D image of the light on the scatter plate during the 0.6 ns period when all beams are on and provides a measure of the directionality of the transmitted power during the period of the interaction.

Demonstration of Energy Transfer

The transmitted probe power waveforms, with and without a pump beam, are shown in Fig. 2, for the case of $\Delta\lambda = 0.43$ nm, and a normalized probe intensity of $I_{probe}/I_{pump} = 0.06$. The total transmitted energy without a pump beam is $49 \pm 7\%$ of the incident energy which is in agreement with a calculation of inverse bremsstrahlung absorption and refraction by the plasma. [7] This transmission is reproducible within ±15%. The shape of the waveform in the pump-off case in Fig. 2 shows that the transmission first increases in time when the plasma temperature is increasing and then decreases in time after the heaters turn off at 1.0 ns and the plasma radiatively cools. Comparison of the waveforms in Fig. 2 shows an increase in the probe's transmitted power during the time the pump beam is on ($0.4 \leq t \leq 1.4$ ns). The pump on waveform is corrected to account for a small variation in the energy of the probe beam between the two shots. The transmitted probe power is nearly the same in the two experiments before the arrival of the pump. After $t = 0.4$ ns, the transmitted probe power rises in about 150 ps to nearly 1.7 times the level observed without the pump, indicating amplification of the probe by the pump. After the pump turns off, the probe power drops rapidly to equal the value observed without the pump. The amplification is determined from the ratio of the two traces and is found to vary between 1.6 and 1.8 during the 1-ns duration of the pump pulse. The average amplification A is determined by averaging over the 1 ns that the pump is on plus an additional 0.3 ns to include the signal delayed by the response of the detector, and is found to be 1.7 in this case.

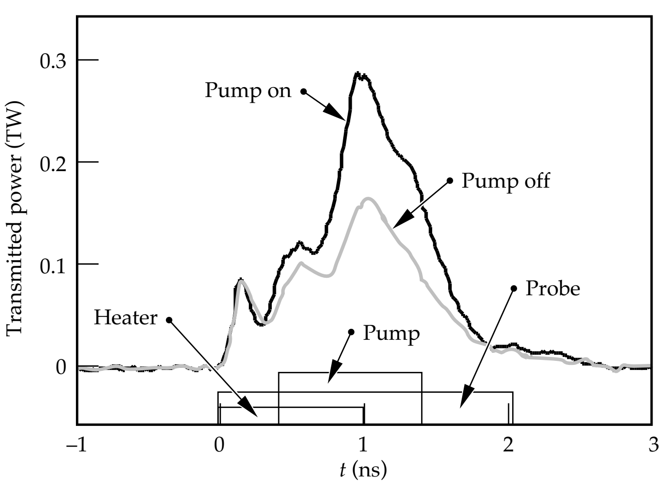

FIGURE 2. Measurement of the probe beam power transmitted through the plasma for the case $\Delta\lambda = 0.45$ nm and $I_{probe}/I_{pump} = 0.06$. In the pump on case, a 2×10^{15} W/cm^2 pump beam intersects the probe between 0.4 and 1.4 ns causing the probe to be amplified by a factor of 1.7 above the pump off case. (08-00-0296-0344pb01)

The amplification observed in Fig. 2 can be explained by scattering from an ion wave produced by the beating of the incident and pump beams. The interaction of the beams creates an ion wave in the plasma, as shown in Fig. 3(a), that scatters energy from the pump so that it propagates parallel to the probe beam, as shown in Fig. 3(b). The ion wave forms in response to the interference of the two beams, which generates a ponderomotive force that is periodic in space and time, and proportional to the product of the amplitude of the two beams. The initial ion wave amplitude is then proportional to the probe beam incident amplitude.

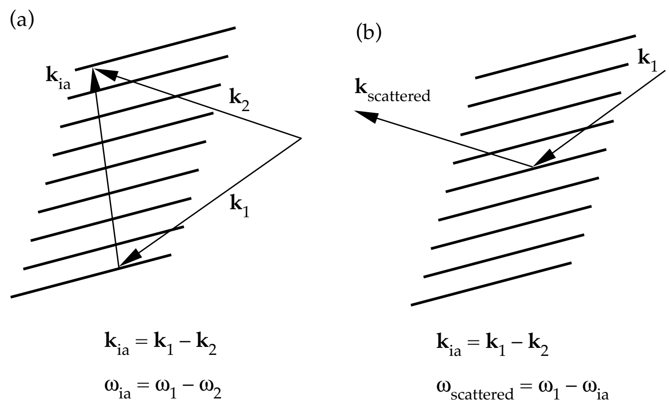

FIGURE 3. (a) Interference of the pump and probe beams creates an ion acoustic wave in the plasma with wave ventor $\mathbf{k}_{ia} = \mathbf{k}_1 - \mathbf{k}_2$ and frequency $\omega_{ia} = \omega_1 - \omega_2$, where $|\mathbf{k}_1| = 2\pi/\lambda_1$ is the wave vector of the pump beam and $|\mathbf{k}_2| = 2\pi/\lambda_2$ is the wave vector of the probe beam. (b) Diffraction of the pump beam off the traveling ion acoustic wave generates a scattered wave with wave vector $\mathbf{k}_{scattered}$ and frequency $\omega_{scattered}$ that is equal to $\mathbf{k}_2$ and ω_2. (08-00-0796-1581pb01)

As a result, the energy scattered from the pump is also proportional to the probe intensity, and an amplification of the probe results. This amplification is defined to be the ratio of the transmitted power measured in an experiment with the pump beam, to that measured in an essentially identical experiment without the pump beam. Resonant interaction requires that the ion wave have a wave vector $\mathbf{k}_{ia}$ which satisfies wave vector matching $\mathbf{k}_{ia} = \Delta\mathbf{k} = \mathbf{k}_1 - \mathbf{k}_2$, where $\mathbf{k}_1$ is the wave vector of the pump and $\mathbf{k}_2$ is the wave vector of the probe. An ion wave with this wave vector will cause energy to be diffracted in the direction of the probe beam. In addition, the scattered wave has its frequency down shifted by the ion wave frequency $\omega_{ia} = c_s\,|\Delta\mathbf{k}|$. Experimental evidence of the wave number matching is obtained from the 2-D image of the transmitted probe beam on the scatter plate. To eliminate the spatial structure in the transmitted beam that is due to the inhomogeneity of the incident beam, the 2-D image is averaged over azimuthal angle to obtain a measure of the beam intensity as a function of the angle from the beam axis, as shown in Fig. 4. The amplified beam has an azimuthally averaged angular profile which is largest inside the $f/4.3$ cone of the incident beam (±6.6°) and similar to the profile of the probe beam obtained when it is transmitted through the plasma with the pump beam off. The fact that the intensity of the amplified beam falls rapidly outside of the $f/4.3$ cone (FWHM = 12°) indicates that the scattering is caused by ion waves with wave numbers near the phase-matched value $\Delta\mathbf{k}$. The profile of the unamplified beam intensity outside the cone is similar to that for the amplified case, indicating that in these experiments the observed spreading of the beam is not caused by the two beam interaction but rather by refraction and scattering from the unperturbed plasma.

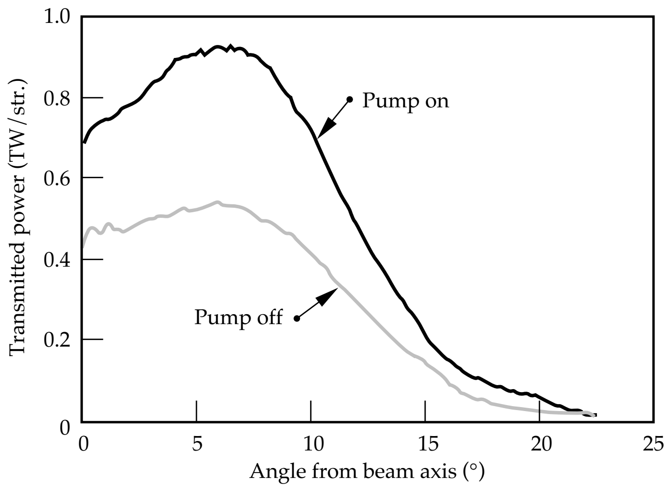

FIGURE 4. The angular distribution of the transmitted power of the probe beam is shown for the experiment in Fig. 2. The similar profiles in the two cases indicate that the amplified light is collimated and coincident with incident laser beam. (08-00-0296-0345pb01)

Determination of the Wavelength Dependence and Maximum Gain

Experiments to determine the average energy amplification as a function of the frequency mismatch were performed for six different pump/probe wavelength separations between 0.0 and 0.73 nm with the normalized probe intensity I_{probe}/I_{pump} between 0.06 and 0.32. The amplifications for these cases are shown in Fig. 5 and exhibit significant gain only when there is a frequency separation between the two beams. The largest amplification is 2.8 when the wavelength separation is $\Delta\lambda = 0.58$ nm. The resonant ion wave frequency is calculated as $\omega_{ia} = c_s|\Delta\mathbf{k}|$ and the half width of the resonance as $\nu_i/2$, where ν_i is the intensity damping rate of the ion wave.[1,8,9] The predicted position of the resonance is $\Delta\lambda = 0.46$ nm with a width of ± 0.04 nm

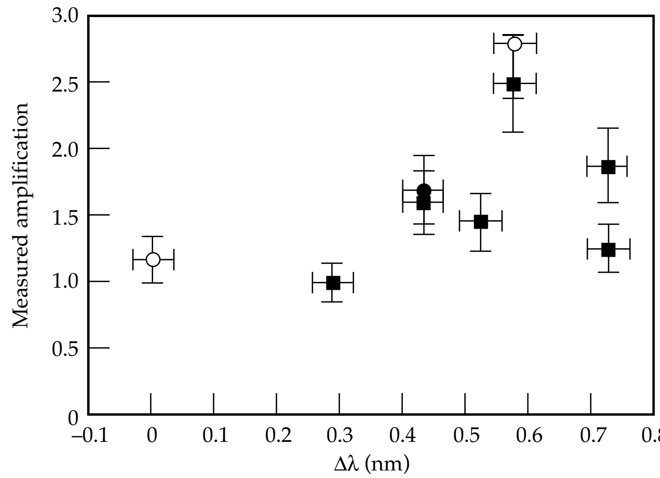

FIGURE 5. A series of experiments measured the amplification of the probe beam as a function of the wavelength separation of the two beams, as shown. The amplification is greatest when the frequency separation is in the vicinity of the unshifted ion wave resonance, $\Delta\lambda = 0.46 \pm 0.04$ nm. Data is shown for I_{pump}/I_{probe} equal to 0.06 (●), 0.13 (■), and 0.32 (○). (08-00-0296-0346pb01).

for the plasma parameters found in the vicinity of the focused beam. This indicates that the observed maximum measured gain is near the ion wave resonance, but may be Doppler shifted by weak plasma flows produced by heater beam and target inhomogenities that are not included in the 2-D simulations. The observation of a maximum amplification near the ion wave frequency combined with the observation of reduced amplification at both larger and smaller frequencies ($\Delta\lambda = 0.3$ nm and 0.73 nm) indicates that resonant excitation of an ion acoustic wave is necessary for amplification.

To compare with theory, we adopt the model of a steady state, convectively saturated instability leading to the amplification A of the probe by a gain coefficient or exponent g such that $g = \ln(A)$. This interpretation is applied in this case for two reasons: (1) the beam crossing angle is < 90° (forward scattering) so that the instability will be convectively saturated in the linear regime, and (2) the duration of the experiment (1 ns) is long compared with the time to reach a steady state, which, in the strong damping limit, is the ion wave damping time (~1.0 ps). The convective saturation of the gain results from the scattered electromagnetic wave propagating out of the interaction region and the ion wave energy being absorbed by Landau damping. The model is extended beyond the standard formulation of nonlinear optics[3] by adding ion wave damping and gain saturation. In the strong damping limit the saturated gain exponent in a homogeneous plasma scales as $nLI_{pump}/(T_e\nu_i)$, where L is the length of the interaction region.[1] According to this model, the pump wave scatters its power in the direction of the probe wave, and the transmitted amplitude is proportional to both the incident pulse wave amplitude and an exponential proportional to the pump wave intensity. The measured amplification is also affected by small scale inhomogeneities both in the incident beam and in the plasma, for which accurate characterization and analysis is presented elsewhere.[1,10] These inhomogeneities make a calculation of the gain of the instability based on the simple model of coherent laser beams in uniform plasmas an over estimate of the actual gain. In fact, under the conditions of this experiment, the ideal model indicates a gain coefficient of $g \approx 20$ when the probe beam is perfectly tuned,[1,8,9] while the maximum observed gain coefficient is $g = 1.0$. This difference can be substantially reconciled by considering calculations, including the two types of inhomogeneities, and recognizing that the set of discrete measurements in Figure 5 may miss the exact resonance and underestimate the peak gain. (1) Because the shape of the resonance is $g \propto 1/[1+4(\Delta\omega/\nu_i)^2]$,[1] a frequency detuning of as little as $\Delta\omega = \nu_i$ (or $\Delta\omega \approx 0.2\ \omega_{ia}$) can decrease g locally by a factor of 5. This frequency detuning can result from Doppler shifting by small amplitude velocity fluctuations in the plasma or by inhomogeneous steady flows, both of which are produced by structure in the laser beam or target. For example, velocity fluctuations as small as $\delta v/c_s \approx 0.2$ rms in the interaction region reduce the gain at resonance by a factor of 3 by Doppler shifting the resonance to different frequencies in different regions of space as discussed in Ref. 1. As shown in Ref. 10, the combination of a spectrum of velocity fluctuations and linear gradients lead to reductions in g by a factor > 5. (2) The gain is reduced by laser beam incoherence. These experiments use RPPs that eliminate large scale structure in the beams, but necessarily create a speckle pattern of small high intensity regions surrounded by large regions of low or zero intensity. The gain of two intersecting beams with RPPs is largely determined by the overlap of the spatial profiles of the two beams. This can lead to a reduction of gain coefficient by an additional factor of 2 or more, depending on details of the beam structure.[10] Clearly, these crossing beam experiments provide a valuable test-bed for motivating and testing improvements to the theory.

Demonstration of Linearity

To investigate the dependence of the scattered power on the incident probe power, experiments were performed at both high- and low-scattered power at the frequency separation of maximum observed gain, $\Delta\lambda = 0.58$ nm. The high-probe intensity was $I_{probe}/I_{pump} = 0.32$ and the low probe intensity was $I_{probe}/I_{pump} = 0.13$. The measured amplification of the probe at high intensity was 2.8 ± 0.42 and at low intensity was 2.5 ± 0.37, indicating that the gain is nearly independent of the probe intensity up to this level and that the ion wave is unsaturated. Under these conditions, a maximum of 52% ± 12% of the pump energy was transferred to the probe. This large an energy transfer should lead to a 23% reduction in the spatially averaged amplification due to pump depletion. This effect was not observed, but it is comparable with the combined shot-to-shot variation in the transmission coefficient (± 15%) and amplification in these measurements.

The amplitude of the ion wave is estimated by considering the amplitude necessary to scatter one half the probe energy in a volume of dimension L, according to the formula $n_1/n_0 = 2/\pi\ (2)^{1/2}\ (\omega/\omega_p)^2\ (L/\lambda_0)$. A lower limit to the maximum ion wave amplitude observed in this experiment is $n_1/n_0 = 1\%$, assuming the scattering occurs uniformly over the region in which the beams intersect ($L = 345$ µm). The actual wave amplitude may be higher if inhomogeneities localize the scatter to a region smaller than L.

The data in Figure 5 indicate a linear dependence of transmitted power on the incident probe power over a wide range if the experiments done at $\Delta\lambda = 0.45$ nm and 0.6 nm are considered. The transmitted power measured with values of I_{probe}/I_{pump} different than 0.13 are normalized to the transmitted power measured at the same $\Delta\lambda$, but with $I_{probe}/I_{pump} = 0.13$. These normalized values are plotted in Fig. 6 and show that the transmitted power is proportional to the incident probe power over a range of 5:1, in good agreement with Ref. 1. At the highest probe intensity, $I_{probe}/I_{pump} = 0.13$, the transmitted power is sufficiently large that a reduction of the gain of approximately 25% is expected due to pump depletion. Although this effect is not apparent in the data in Fig. 6 it is about the same order of magnitude as the indicated error bars and is probably not observable in these experiments.

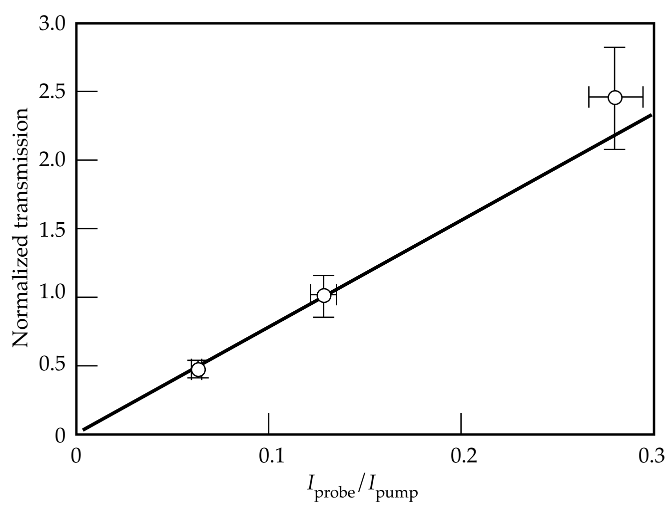

FIGURE 6. The measured transmitted power is shown to be proportional to the probe intensity over the range of $I_{probe}/I_{pump} = 0.06$ to 0.32, using data obtained at disparate separation frequencies by normalizing to the amplification measured with $I_{probe}/I_{pump} = 0.13$. (08-00-0296-0347pb01)

Conclusions

We report the first observation of energy transfer between frequency-mismatched laser beams in the presence of a stimulated ion acoustic wave. The effect is shown to be linear with probe beam intensity, indicating that there is no saturation of the ion wave up to a maximum of 52% energy transfer in these conditions. We also show that energy transfer occurs only when the beams are not symmetric and is maximized when the difference in the wave frequencies in the plasma frame is near the frequency of the resonant ion acoustic wave. Although it is expected that the flowing plasmas present in NIF targets may Doppler shift the frequencies of the incident beams so that they satisfy the resonance conditions, this experiment demonstrates that the transfer of energy may be controlled by adjusting the wavelengths of the incident beams.

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